Zooplankton Aggregation Near Sills

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LONG-TERM GOALS

Improved knowledge of the physical and biological mechanisms and interactions responsible for forming and maintaining aggregations of biological sound-scatterers in the ocean.

OBJECTIVES

Dense aggregations of plankton and fish often occur in localized regions where ocean currents interact with steeply sloping seabed. These sites are ecologically important 'hot spots' for prey-predator trophic interactions, and are also zones of very strong acoustic backscatter. Our project examines the biological and physical mechanisms responsible for forming, maintaining and dispersing zooplankton aggregations near the sill of Knight Inlet, a large fjord in British Columbia (sill at 50º41'N 126º00'W).

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APPROACH

We combine new field measurements (2001, 2002) with retrospective analyses of acoustic and physical oceanographic data from the mid 1990s. Our field sampling is multidisciplinary, linking fine-resolution acoustic data with *in situ* physical and biological measurements. Sampling tools include: ship-mounted multi-frequency acoustics to map cross-sill vertical and horizontal distributions of back-scatter intensity and horizontal velocity (drift + swimming); an instrumented multiple plankton net (BIONESS) and an optical plankton counter (OPC) for zooplankton abundance, species composition, and body size/shape; a high resolution digital camera for zooplankton body/swimming orientation; CTD and transmissometer to describe temperature, salintiy, and turbidity fields; and a moored acoustic doppler current meter (ADCP).

Choice of study site is an important element of our approach. Aggregations of sound scatterers are associated with a variety of bathymetric 'edges', including continental shelf break and slope regions (e.g. Simard and Mackas 1989; Mackas et al. 1997; Swartzman et al. 1999) and the margins of shelf banks and basins (Coyle et al. 1992; Haury, Briscoe and Orr 1979), submarine canyons (Allen et al. 2001, Greene et al 1988, Mackas et al. 1997), seamounts, and the edges, sills and headwalls of steep-sided inlets (Simard et al. 1986, Simard and Lavoie 1999, Romaine et al. 2002). However, most of these settings are hydrodynamically complex. We have selected as experimental site the region surrounding the Knight Inlet fjord sill. This site provides (at least by oceanic standards) a very well-defined observational environment: strong cross-isobath flow that is predictably time-varying at semidiurnal, diurnal and fortnightly time scales, weak along isobath flow, clearly identifiable upstream and downstream locations and populations. There is also much information from previous research programs (e.g. Farmer and Armi 1999).

A final (and new) element of our approach is a simulation model examining how zooplankton behavior interacts with bathymetry and vertically sheared tidal currents to produce the aggregations. The model allows us to test alternative ‘behavior’ scenarios by comparing model output with observed formation rates and locations of the aggregations.

Expertise and project responsibilities of the lead investigators are:
- D. Mackas: biological oceanographer and zooplankton ecologist with expertise on zooplankton spatial pattern. Responsible for overall coordination of field surveys (Nov 2001 and Nov 2002), net tow sampling, CTD sections, and the ADCP mooring.
- M. Trevorrow: acoustician and physical oceanographer. Responsible for most acoustic measurements.
- M. Benfield: biological oceanographer and zooplankton ecologist with expertise on optical imaging. Responsible for the high-resolution digital camera.
- D. Farmer: physical oceanographer and applied acoustician. Has provided interpretation of Knight Inlet physical oceanography, and access to data from prior surveys.

Additional year 3 participants in the project (not funded by ONR) include:
- S. Allen (University of British Columbia) and D. Ianson (IOS): development of numerical model.
- D. Yelland and D. Tuele (IOS): oceanographic field support, mooring deployments, and processing of acoustic and CTD data.
- M. Tsurumi (NSERC post-doctoral fellow, IOS and UBC): biological oceanographer, working on ecological interpretation of aggregation dynamics

- R. Campbell (PhD. student, University of Victoria): collection and analysis of OPC profiles

WORK COMPLETED

Year 1 (Jan-Sept 2001)
Three activities (reported in greater detail in previous annual reports):
1) Retrospective analyses of acoustic data from earlier surveys of Knight Inlet
2) Purchase and testing of the three-frequency downward-looking echosounder.
3) Planning and booking of ship time

Year 2 (Oct 2001-Sept 2002)
The major project activity was staging, execution, and analysis of data from the year 2 field survey (CCGS VECTOR 12-26 November 2001), and development of plans for the year 3 field work. See previous annual reports for additional detail.

Year 3 (Oct 2002-Sept 2003)
We completed a second field survey (CCGS VECTOR, 11-25 November 2002). Important additions to the field program were multi-beam acoustic sensors allowing swath mapping of both sill bathymetry and the midwater zooplankton patches (see Trevorrow report), and use of a small otter trawl to sample the predator aggregations (prawns and fish) which occur at the upstream crest of the sill where they exert heavy predation pressure on zooplankton aggregations advected toward and over the sill (see Results). ONR funding under #N00014-01-1-0274 covered 50% of ship costs; shared purchase of an RDI acoustic doppler current profiler; collection and processing of zooplankton net tow samples (55), trawl samples (2), along inlet CTD section (20 stations), and ADCP data (2 week deployment); and maintenance and upgrades to BIONESS and ship-mounted and moored acoustic sensors. We also contributed data and ideas to the numerical model of aggregation formation, and provided the net-tow, OPC, and CTD profiles used by Trevorrow to calibrate the multi-frequency echosounder.

RESULTS

1. Physical setting
Knight Inlet is a deep, and relatively uniform-width fjord. 35 km from the mouth is a 60 m deep sill restricting flow between a very deep inner basin and a shallower outer basin (Fig 1). Melt-water from several ice fields strongly affects both salinity and turbidity fields throughout the year.

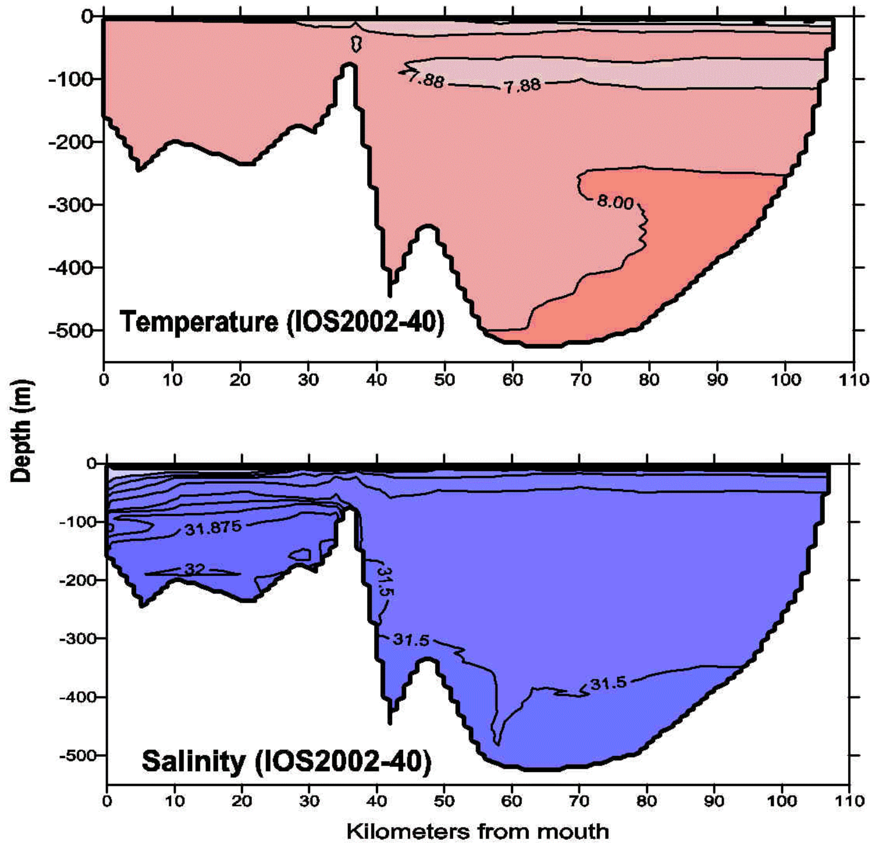

Figure 1: Along-inlet sections of temperature and salinity, November 2002. The mouth (west) end of the inlet is at the left, the head of the inlet (northeast) is at the right, and the sill is between km 35-36.

2. Broad-scale distribution of euphausiids in Knight Inlet

Euphausiids are the dominant zooplankton and the main source of 120kHz acoustic backscatter near the Knight sill. During our surveys in both years, net tows and acoustic transects showed a very intense, but very localized, euphausiid maximum in the immediate vicinity of the sill. This localized maximum (typically 1-2 km along inlet dimension) is embedded in a larger-scale broad minimum. Concentrations at locations ~2-10 km from the sill averaged about an order of magnitude lower than those within the sill-margin maximum, and about a factor of 2-3 lower than at locations 20-30 km from the sill (see 2002 report for examples).

3. Interactions Between Zooplankton and Tidal currents

The dominant currents in Knight Inlet are the semi-diurnal tides, with tidal range from 1 to 4.5 m. The flood tide runs eastward (Fig 2 top).

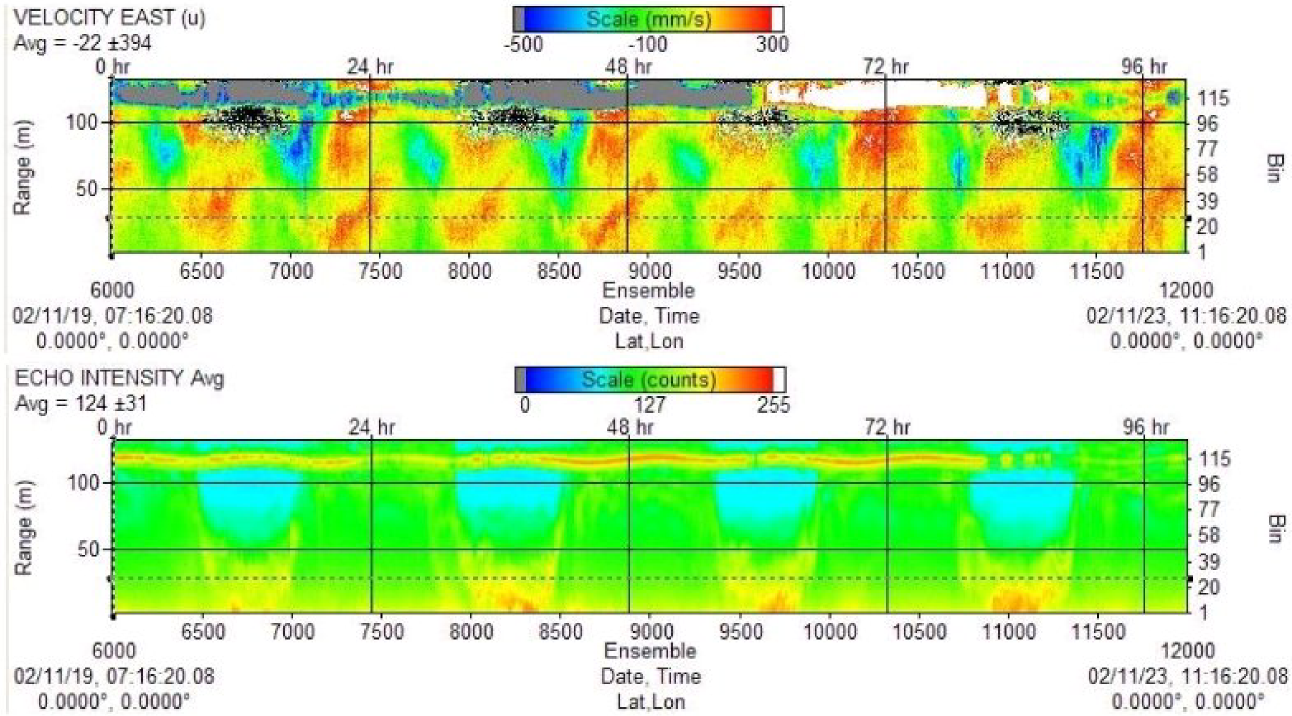

Fig. 2. Time series of along inlet currents (top, orange-red = flood) and backscatter intensity (bottom, orange-red = strong) from an ADCP moored west of the sill (110 m instrument depth). Peak aggregations on the west side of the sill occurred near the end of daytime flood tides.

Euphausiid aggregation density is modulated on two relatively short time scales (Fig 2 bottom): day-night (due to vertical migration of the euphausiids) and tidal (the aggregations build on opposite sides of the sill, during alternating phases of the flood-ebb cycle)

The along inlet spatial pattern is quite distinctive (Fig. 3). The scattering layer is advected with the tidal flow, but intensifies and deepens as it approaches the sill. We are experimenting with a numerical model of this aggregation process. All results are consistent with a hypothesis that aggregation is by a process of convergence where the scattering layer begins to intersect the turbulent but slower-moving benthic boundary layer. A 'downward' behavioural response to boundary layer turbulence appears responsible for the deepening of the aggregation very near the sill, and also intensifies the efficiency of the aggregation.

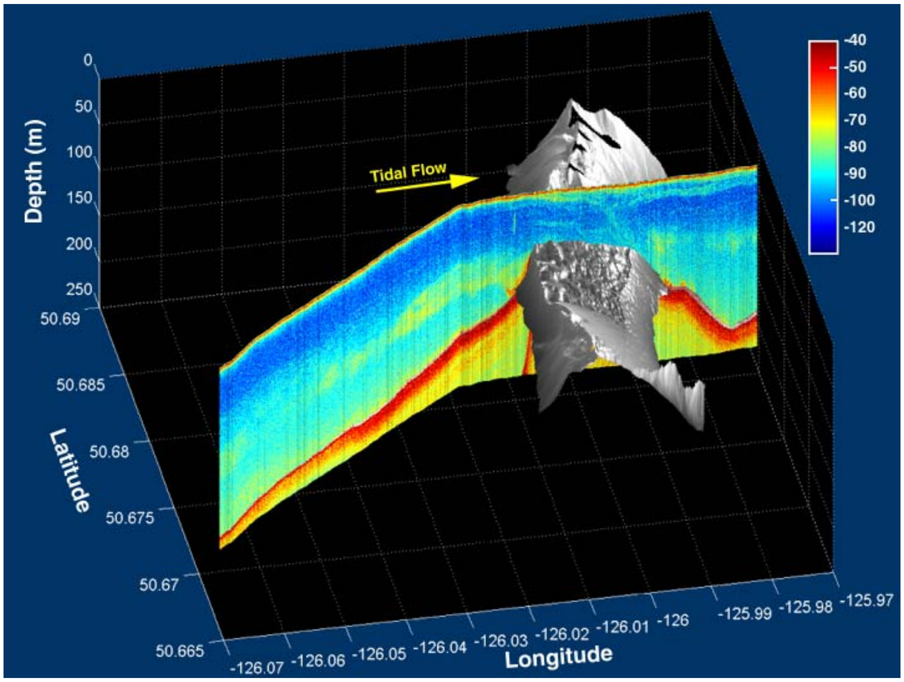

Fig. 3. Along inlet profile of euphausiid scattering layer intensity during a flooding tide (colored 'panel') shown intersecting the sill bathymetry ('silver' 3D form, from multibeam survey by M. Trevorrow). The scattering layer extends upstream of the sill, but intensifies and deepens close to the sill. (Graphics courtesy M. Benfield)

4. Interactions Between Zooplankton and Predators

We suspect that a cause of the broader scale minimum in euphausiid abundance is intense predation at the sill. The sill is a good foraging site for visual predators because each tidal cycle produces a daytime midwater aggregation of euphausiids along the upstream face of the sill. Because we had a three-frequency echosounder system (38kHz, 120kHz and 200 kHz in 2002), we were able to discriminate among targets based on differences in body size. We regularly observed dense daytime aggregations of larger acoustic targets at the crest of the sill. A tow through this layer with a small otter trawl produced a large catch (Fig 4) of planktivorous prawns and finfish and, despite the coarse mesh of the trawl, large numbers of euphausiids. Location of the 'predator' aggregations shifted from inshore to offshore side of the sill with tidal phase, but appeared to anticipate the change in tidal current direction.

Fig. 4. Catch of a small otter trawl towed along the face of the sill. Abundant prawns and finfish (left) coincided with a dense euphausiid aggregation (right)

IMPACT/APPLICATIONS

Results of the retrospective analysis have been published as a DREA Data Report (Trevorrow 2001). An initial interpretation of the 2001 results was presented at the October 2002 PICES/GLOBEC conference in Qingdao, China (Trevorrow et al. 2002). Combined 2001-2002 field survey and modelling results have been presented at the 2003 Estuarine Research Foundation conference (Benfield et al. 2003) and at the 2003 PICES conference (Mackas et al. 2003, Allen et al. 2003).

REFERENCES & *PUBLICATIONS*

Allen, S.E., C. Vindeirinho, R.E. Thomson, M.G.G. Foreman and D.L. Mackas. 2001. Can. J. Fish. Aquatic Sci. 58: 671-684.

Allen, S.E., D. Ianson, D.L. Mackas, M.V. Trevorrow, and M. Tsurumi. 2003. Modelling zooplankton aggregation due to tidal flow over a sill. PICES XII conference (published abstract).

Benfield, M.C., Trevorrow, Mackas, Yelland, Keenan, Tsurumi, Campbell and Tuele. 2003. Biophysical focusing of zooplankton at a fjord sill. Estuarine Research Federation conference (published abstract).

Coyle, K.O., G.L. Hunt, M.B. Decker and T. Weingartner. 1992. Mar. Ecol. Prog. Ser. 83: 1-14.

Farmer D. and L. Armi. 1999. Proc. Roy. Soc. A. 455: 3221-3258.

Greene, C.H., P.H. Wiebe, J. Burczynski and M. Youngbluth. 1988. Science 241: 359-361.

Haury, L.R., M.G. Brisscoe and M.H. Orr. 1979. Nature 278: 312-317.

Mackas, D.L., R. Kieser, M. Saunders, D.R. Yelland, R.M. Brown and D.F. Moore. 1997. Can. J. Fish. Aquatic Sci. 54: 2080-2096.

Mackas, D.L., M.V. Trevorrow, D.R. Yelland, M. Tsurumi, and M. Benfield. 2003. Observations of zooplankton aggregation due to tidal flow over a sill. PICES XII conference (published abstract).

Romaine, S., D. Mackas and M. Macaulay. 2002. Fisheries Oceanogr. 11: 102-115

Simard, Y., R. deLadurantye and J.-C. Therriault. 1986. Mar. Ecol. Prog. Ser. 32: 203-215.

Simard, Y. and D.L. Mackas. 1989. Can. J. Fish. Aquatic Sci. 46: 1238-1249.

Simard, Y. and D. Lavoie. 1999. Can. J. Fish. Aquatic Sci. 56: 1182-1197.
Swartzman, G., R. Brodeur, J. Napp, G. Hunt, D. Demer and R. Hewitt. 1999. ICES J. Mar. Sci. 56: 545-560.
Trevorrow, M., 2001. Zooplankton aggregations near a coastal sill: an examination of echo-sounder data from August and September 1995 in Knight Inlet, B.C. DREA Technical Memorandum 2001-119, Defence Research Establishment Atlantic, Dartmouth, NS, 35 pages.
Trevorrow, M, D. Mackas, D. Yelland and M. Benfield. 2002. Aggregation of macrozooplankton and fish at a fjord sill. PICES XI conference (published abstract).